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| <p>A panel of 30 scientists and engineers from 7 countries evaluated the present status of research involving polarization diversity radars and made recommendations for the future of this specialty. Polarization diversity radar techniques have been shown to be of great value for deriving microphysical characteristics of clouds and precipitation. The most critical issues pertaining to research with polarization diversity radars are (1) to use existing radars more effectively in research, (2) to improve the verification of radar measurements, and (3) to develop improved radar facilities. It is essential that specialists in polarization diversity radar technology interact with meteorologists and engineers in a wide range of specialties to guide the development of polarimetric radar facilities and techniques.</p> |       |   |   |  |                           |
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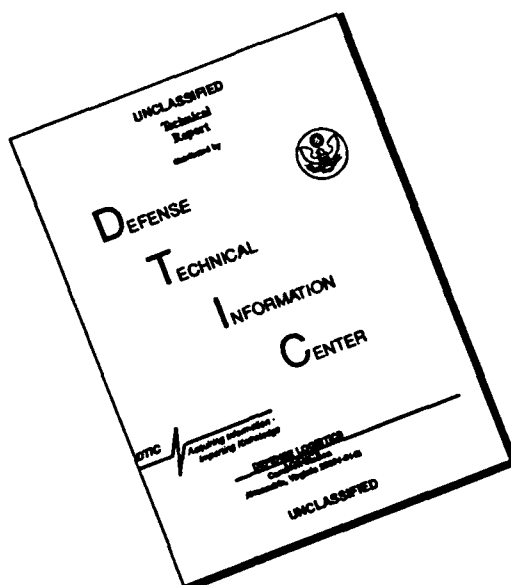
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## Chapter 19b

# Technology of Polarization Diversity Radars for Meteorology: Panel Report

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## 1 INTRODUCTION

From the earliest years of meteorological radar research, the potential utility of polarization techniques was recognized by several research organizations. Their experimental and analytical endeavors are described by Seliga et al. (Chapter 14). The polarization dependence in the response of a meteorological radar is determined by the anisotropic character of most cloud and precipitation particles. Consequently, through analytical or empirical models, the measured quantities can be related to sizes, shapes, orientations, or thermodynamic phases of hydrometeors in the propagation or backscatter media.

Polarization diversity radar techniques are therefore valuable for deriving microphysical characteristics of clouds and precipitation. These techniques can contribute to a variety of research topics and applications: hydrometeor evolution, precipitation development, cloud electrical phenomena, quantitative rainfall measurement, discrimination of ice and liquid water in clouds, hail detection, aircraft icing detection, and the description of microwave and millimeter-wave propagation in clouds and precipitation. In combination with Doppler radar techniques, polarization techniques can contribute significantly to the development of conceptual models of cloud and precipitation systems.

However, the promise of polarization diversity radar technology can only be realized if several challenges are

met. Foremost among these is the need for expanded interaction between radar specialists and the broader scientific community. To view polarimetric radar technology as the exclusive domain of specialists is to raise a barrier to the interdisciplinary work that is needed to develop broader understanding of the value of this technology in meteorological research and applications. The vitality of this scientific interaction has an impact on a variety of other issues, including effective verification of polarimetric radar measurements, planning for the development and use of facilities, and application to operational needs. In this report we discuss these and other issues that will shape the future development and use of polarimetric radar techniques. Advancement of the technology and its applications will rely also on the advancing technology of signal processing, which is discussed in Chapters 20a and 20b. Interpretation of polarimetric radar measurements in cloud physics is discussed further in Chapters 23a and 23b.

## 2 PRESENT CAPABILITIES

In the past decade there has been a significant increase in the number and capability of polarization diversity meteorological radars. Of the 21 polarimetric radars discussed in the accompanying review by Bringi and Hendry (Chapter 19a), 14 were either new or modified for polarimetric measurements within the past ten years and 8 within the past five years. Some of these radars have undergone further modification to provide more flexibility. These developments collectively support the assessment that the state of the art of polarization diversity meteorological radars includes at least 1) simultaneous coherent reception of two orthogonal polarizations, and 2) rapid switching of the transmitted signal between two orthogonal polarizations. It has been suggested that these attributes are sufficient for a complete measurement of partially polarized backscatter from meteorological media, provided that the choice of polarizations is such as to yield a measurable signal in each channel of the receiver. The state of the art is further defined by the characteristics of the best polarization switches, antennas, receivers, and data systems now in use.

\*Metcalf served as leader of this panel. Other members were Kulagin (Ardur, Pennsylvania State University), N. Balakrishnan (National Severe Storms Laboratory), Wolfgang-Martin Boerner (University of Illinois), V.N. Bringi (Colorado State University), Marx Brook (New Mexico Institute of Mining and Technology, retired), Madhukar S. Chandra (DFVLR, West Germany), Charles Frush (NCAR), Spiros Geotis (MIT), Eugenio Gorgucci (IFA, Italy), Archibald Hendry (National Research Council, Canada, retired), Paul Herzegh (NCAR), Anthony R. Holt (University of Essex, United Kingdom), Robert G. Humphries (MacDonald Dettwiler, Canada), Anthony Illingworth (University of Manchester, United Kingdom), Arthur R. Jameson (Applied Research Corp.), Paul Korb (New Mexico Tech), Leo P. Ligthart (Technische Universiteit Delft, The Netherlands), G.C. McCormick (NRC, retired), Raymond McGuinness (University of Essex), Eugene Mueller (Illinois State Water Survey), Reginald Newell (MIT), Tomohiro Oguchi (Communications Research Laboratories, Japan), Fausto Pasqualucci (Hughes Aircraft Co.), Gianfranco Scarchilli (IFA), Arno C. Schroth (DFVLR), Thomas A. Seliga (Pennsylvania State University), Enrico Torlaschi (Université du Québec à Montréal), James S. Ussailis (Ussailis Engineering), and Fumio Yoshino (Public Works Research Institute, Japan).

Much of the recent interest in polarimetric techniques is due to the expectation that the use of the differential reflectivity between horizontally and vertically polarized signals would yield improved quantitative measurement of rainfall. This power ratio, which was described by Seliga and Bringi (1976), is now the most commonly measured polarimetric quantity. Several experimental programs have shown improvement of rainfall measurement with this technique, especially at moderate or greater rainfall rates and at relatively short ranges (e.g., Goddard et al., 1982; Aydin et al., 1987). Some uncertainties remain, however, about its quantitative interpretation (Bumgarner and Dooley, 1986; Yoshino et al., 1987). The differential reflectivity appears to be a good indicator of the presence of the ice phase, particularly the presence of hail in convective storms (e.g., Aydin et al., 1986). The interpretation of measurements of low density ice particles, which have a smaller effective value of dielectric constant than raindrops, is more difficult. Two recent studies involving comparison of measurements by radar and by airborne particle instruments (Liu and Herzegh, 1986; Bader et al., 1987) showed that if only the absolute and differential reflectivities are available then there are ambiguities in the particle type inferred from the radar data.

The recent development of theory for interpreting polarimetric meteorological radar measurements has more than kept pace with the availability of corresponding measurements. For example, McCormick (1979) described the derivation of differential reflectivity from measurements with circular polarization, and Bebbington et al. (1987) improved that derivation with a correction for propagation differential phase shift at 10-cm wavelength. Jameson (1987) and Jameson and Davé (1988) showed the possibility of deriving from measurements with linear polarization the quantities usually measured with circular polarization and vice versa. Jameson and Davé also described a technique by which the cross-covariance of the two copolar amplitudes  $E_{HH}$  and  $E_{VV}$  measured by a "differential reflectivity" radar could be used to correct a bias in median volume diameter  $D_0$  estimated from measurements of differential reflectivity. Metcalf (1986) showed the possibility of using all the Doppler parameters available from a dual-receiver radar to gain increased information on the microphysics of the backscatter medium. The recent work of Schroth et al. (1988) presents the case for nearly simultaneous measurement of the four complex amplitudes that constitute the scattering matrix ( $S$  matrix) and for computing all the covariances among them. Schroth et al. also emphasize that the covariances involving products of amplitudes from oppositely polarized transmissions, e.g.,  $E_{HH}$  and  $E_{VV}$ , must be corrected for the phase shift that arises from the mean motion of the scatterers during the interpulse period.

Several radars are capable of generating all the data necessary to implement or evaluate the latest theoretical

developments. The 5-cm (C-band) radar at the Deutsche Forschungs- und Versuchsanstalt für Luft und Raumfahrt (DFVLR) in West Germany is an outstanding example. Some other radars have nearly complete capability, in that they lack only rapid switching or receiver coherence. The most flexible data systems, such as that of DFVLR, have easily accessible options either to record averages of powers, covariances, and Doppler mean velocities and spectrum variances computed in real time or to record time series data at multiple ranges for off-line analysis and algorithm development. Some polarimetric radars are capable of measuring a limited subset of the quantities of interest; e.g., differential reflectivity or linear depolarization ratio or both. Some of these can also measure the Doppler mean velocity and spectrum variance.

In the United States the 3- and 10-cm (X- and S-band) CP-2 polarimetric radar operated by the National Center for Atmospheric Research (NCAR) has been particularly well used for several years. It was a key sensor of the May Polarization Experiments (MAYPOLE) in Colorado in 1983 and 1984; the Classify, Locate, and Avoid Wind Shear (CLAWS) Project in Colorado in 1984; the Microburst and Severe Thunderstorm (MIST) Project in Alabama in 1986; and the Convective Initiation and Downburst Experiment (CINDE) in Colorado in 1987. The latter three projects were designed to investigate the origins and development of downbursts and microbursts in convective storms. Earlier research results suggested that these downward air motions are related to the cloud microphysics through melting and evaporative cooling of downward-moving air in the cloud (e.g., Srivastava, 1985). These projects provided opportunities to investigate this relationship and other aspects of storm microphysics and to expand the polarization diversity database. Although the CP-2 radar was added to MIST reluctantly and late in the planning, its data have already yielded clues to possible microphysical precursors of downbursts (Wakimoto and Bringi, 1988). Analysis of triple-Doppler radar data from MIST has revealed columns of positive differential reflectivity extending well above the 0°C isotherm coincident with updrafts (Tuttle et al., 1989). At present the CP-2 radar is used by the National Oceanic and Atmospheric Administration (NOAA) in its Program for Regional Observing and Forecasting Services (PROFS). Techniques are being developed to use absolute and differential reflectivities for discrimination of ice and liquid water in clouds.

The 10-cm Chilbolton radar in the United Kingdom has been used in coordination with the C-130 aircraft operated by the British Meteorological Office (e.g., Bader et al., 1987), and this radar participated in the joint Anglo-French Mesoscale Frontal Dynamics Project from October 1987 to January 1988. It is currently being used to gather statistical data for a tropospheric radio propagation study, operating continuously (24 hours per day) for two weeks every month. During the intervening times it is available

for measurements of differential reflectivity, linear depolarization ratio, and time series of received signals for more direct meteorological applications.

Some existing polarimetric radars have not been used adequately in recent years. For example, the 10-cm radar formerly operated by the Alberta Research Council has been unfunded for routine operations since 1985; it may be acquired by another research organization. The 8.6-mm ( $K_u$ -band) and 3-cm radars of the NOAA Wave Propagation Laboratory have been used on an occasional basis, mainly in externally funded programs. The 3-cm radar formerly operated by the National Research Council (NRC) of Canada faced an uncertain future until it was leased to MPB Technologies, Inc. of Montréal. While the immediate reason for this underuse is a lack of funding, the present disuse of the Alberta radar and the leasing of the NRC radar are related to recent organizational changes that eliminated the primary mission for each of these radars. These and other radars that have seen extensive use in the past have generated datasets that are of great intrinsic value but that are also underused. The latter phenomenon results from lack of funds to support analysis, both in the host organizations and in other funding organizations, and lack of awareness of the data on the part of prospective investigators.

In summary, we believe that substantial progress has been made in recent theoretical developments and that excellent measurement capabilities are inherent in presently available radar technology. On the other hand, we are concerned that this technology is not being used effectively in many places. Our concern extends both to radars having performance characteristics of lower quality than is available and to radars that are not being fully used, some of which have very good antenna characteristics, high quality data systems, or other desirable attributes.

### 3 ISSUES AND RECOMMENDATIONS

The fundamental objective toward which the use of polarimetric radars must be directed is an increased understanding of physical processes in clouds. Because radars can sample large volumes of the atmosphere rapidly and repeatedly, polarimetric radars can facilitate the study of cloud physical processes on the scale of a whole cloud or a mesoscale weather system. This increased knowledge of cloud processes and the continuing improvement of radar equipment and techniques will contribute to a variety of practical applications, as suggested in the Introduction.

The most critical issues are (i) the more effective use of existing radars in research, (ii) improved verification of radar measurements, and (iii) technological improvement of meteorological radars. In the following paragraphs we discuss these and other issues in detail.

#### 3.1 Meteorological Research

Our primary concern, particularly in the near future, is that existing radars be used with maximum effectiveness. Some technical objectives can be met through the use of individual radars in locally staged experimental programs. Other objectives require the use of polarimetric radars in multisensor field measurement programs, which generally offer the best opportunity for verification of radar measurements.

The use of polarimetric radars in large field programs, even those with specific objectives related to cloud physics, has been irregular at best. The radar of the Alberta Research Council, for example, was used considerably in a multisensor environment with coordinated observations by instrumented aircraft, but it was almost always operated in a full-volume scanning mode required for the hail suppression program, which was its primary mission. The radars of NRC—the 1.8-cm ( $K_u$ -band) radar until 1980 and the 3-cm radar from 1981 to 1987—were almost always operated without ancillary data sources. In 1981 the 3- and 10-cm CHILL radar of the Illinois State Water Survey (ISWS), newly modified for pulse-to-pulse polarization switching, and the new 8.6-mm radar of NOAA were both involved in the Cooperative Convective Precipitation Experiment (CCOPE), but because their polarimetric capabilities were new and untested their use in that experiment was largely limited to evaluation by polarimetric meteorological radar specialists.

Several major programs in which measurements with polarimetric radars will be particularly valuable are now under way or being planned in the United States. One is the National Plan to Improve Aircraft Icing Forecasts developed by the U.S. Federal Coordinator for Meteorological Services and Supporting Research, which includes measurement programs during the winters of 1987/88 and 1989/90 in Colorado. A variety of remote and in situ sensors are used in this program, but no polarimetric radars were used during the first winter. Use of the polarimetric radars of NOAA in 1989/90 appears likely. The Tropical Rainfall Measurement Mission (TRMM), sponsored by the National Aeronautics and Space Administration (NASA) with the goal of improving the global remote measurement of rainfall in the tropics, offers a particularly valuable opportunity for polarimetric radar measurements. This program is generating specific needs for ground-based instrumentation, including radars, at several sites in the tropics, and it offers an unusual opportunity to acquire a long-duration database and to refine the application of polarimetric techniques to the problem of rainfall measurement. In addition to supporting the objectives of TRMM, suitably placed polarimetric radars will be able to acquire data relating to the microphysics of precipitation development, the electrification of convective clouds, and electromagnetic propagation characteristics. The Stormscale Operational and Research Meteorology (STORM) Program field ex-

periment planned for the early 1990s in the central United States (STORM-Central) presents another opportunity for the advantageous use of polarimetric radars. The polarimetric radar at the National Severe Storms Laboratory (NSSL) will be of great value in this experiment for documenting microphysical processes and estimating rainfall, as it measures the differential reflectivity, the differential phase shift, and the copolar cross-correlation of horizontally and vertically polarized signals. The results of STORM-Central would be further enhanced by the inclusion of polarimetric radars having full matrix measurement capability, which would aid the study of microphysical and electrical processes in mesoscale convective systems.

In addition to the use of polarimetric radars in multi-sensor field programs, these radars have important roles in more modest measurement programs. For example, a radar under the control of a single research organization can be used to acquire a long-term record of observations in a local area. Such a radar can provide more flexibility for the developing and testing of new components and techniques than can a radar that must be scheduled for limited observational periods far in advance. Other topics suitable for investigation by means of locally managed facilities include the effects of electric fields on hydrometeors, first observed by McCormick and Hendry (1976), and the use of chaff to reveal entrainment in clouds, as described by Moninger and Kropfli (1987). The radars of NRC exemplify this category of facility. Other examples are the 10-cm radar at Air Force Geophysics Laboratory and the 3-cm radar at New Mexico Institute of Mining and Technology, both of which have been used to advantage with and without extensive ancillary measurements.

### 3.2 System Performance and Measurement Accuracy

The theory of polarimetric meteorological radar measurements has progressed to at least our partial understanding of the physical significance of all the presently defined quantities measurable by radar. Major advances have occurred both in the specification of these quantities; e.g., the terms of the backscatter matrix ( $S$  matrix) and the power averages and ratios, autocorrelations, and cross-correlations derivable from those terms, and in the derivation of meteorological information from them. There are continuing needs for theoretical and experimental investigations to define the effects of radar system attributes on the measured quantities and to specify the accuracy with which the quantities must be measured for useful interpretation.

Measurements must be taken to determine the levels of system performance required to obtain useful measurements of polarimetric quantities. Radar system attributes such as cross-polarization isolation, radiation pattern, angular scan strategy, calibration accuracy, polarization switching rate, sampling interval, and signal averaging time

must be examined. The effects of antenna pattern mismatch between orthogonal polarizations and the effects of sidelobes have received some attention in the recent past (e.g., Herzeg and Carbone, 1984). Some of the resulting artifacts are easily recognized, but we need to be able to identify the less obvious effects. The measurement of the sidelobe pattern and the analysis of its effects on measurements are not trivial tasks. More effort must be devoted both to understanding these effects more fully and to minimizing them through the use of high quality antennas. Familiarity with recent work such as that of Kildal et al. (1988), which describes the effects of feed support struts on copolarized and cross-polarized sidelobe levels, is essential to optimum antenna design. We expect that all these investigations will contribute to improved derivation of meteorological information and to the specification of polarimetric radars for operational purposes.

Statistical analysis has been accomplished for some of the measured quantities, such as differential reflectivity (Brangi et al., 1983; Sachidananda and Zrnić, 1985) and differential phase shift (Sachidananda and Zrnić, 1986). The first measurements of differential phase shift (Sachidananda and Zrnić, 1987) showed fluctuations as large as  $\pm 5^\circ$ , despite their theoretical estimate of about  $\pm 0.5^\circ$  standard error. Such a large error effectively masks any useful information on the raindrop-size distribution. Sachidananda and Zrnić suggest that the degradation may be due to backscatter in the sidelobes. However, the large standard deviation may be due to the different phase velocities of electromagnetic propagation modes in large, oscillating raindrops. The source needs to be identified and quantified. Other quantities must be similarly analyzed, to determine the time scales necessary for their measurements and to determine the relative accuracy of meteorological parameters derived from them. For example, the required accuracy of measurement of circular depolarization ratio and cross-correlation for derivation of differential reflectivity should be evaluated. The result will help to determine the relative advantages of using a dual-channel circularly polarized radar or a fast-switching single-channel linearly polarized radar.

Polarimetric measurements have traditionally been based on the derivation of power ratios and cross-correlations between orthogonally polarized signals. These quantities have been interpreted individually or jointly in terms of meteorological parameters; e.g., thermodynamic phase, raindrop size, ice crystal habit, and mean apparent canting angle. The  $S$  matrix terms and derived parameters, previously discussed, and other representations, such as the Huynen Polarization Fork in the Poincaré Sphere can also be interpreted in terms of meteorological parameters. In addition, it has been suggested that adaptive polarization techniques may be useful to compensate for propagation effects in observations at long ranges through precipitation and to prevent saturation in the radar receiver due to nearby reflections. Further theoretical studies must be

conducted, and ultimately supported by measurements, to determine the relative merits of these approaches.

Propagation effects are significant at wavelengths shorter than about 5 cm. The possibility of compensating these effects in radar measurements and thereby deriving valid characterization of the backscatter medium at these wavelengths is a subject requiring both theoretical and experimental investigation. Recent measurements at DFVLR and elsewhere hint at nonreciprocal propagation effects in electrified clouds. Calculations by Oguchi (1988) suggest possible effects of multiple scattering in the propagation of millimeter and shorter wavelengths through rain. Understanding these phenomena is particularly important if radar of multiple wavelengths are to be used with maximum effectiveness for atmospheric research.

In addition to the objectives described above, there is a need to refine and standardize the nomenclature and notation of polarimetric meteorological radar measurements. Various conventions have emerged from the diverse roots of this technology; e.g., meteorology, signal propagation, radar engineering, and radar cross-section measurement. Assumptions and approximations that have been incorporated into some of the analytical formulations in some cases limit the accuracy or completeness of the results. Kostinski and Boerner (1986) and Boerner and Kostinski (1988), for example, have taken steps toward improved fundamental understanding of polarimetric theory and formulation.

### 3.3 Verification Studies

The quantities measured by a polarimetric radar are influenced by the shape, orientation, thermodynamic phase, density, and size distribution of hydrometeors. Also, attributes of a radar system such as antenna pattern mismatch and calibration errors may introduce subtle distortions of measured quantities. Because measurements of any polarimetric quantity generally contain contributions from several of these factors, interpretation of radar measurements frequently involves choosing among several interrelated possibilities. As a result, verification measurements are necessary to establish "benchmark" information for use in the interpretation of radar data or in testing the results of theoretical work.

Verification studies for rainfall rates and raindrop shapes have given us some confidence in the use of polarization techniques for estimating rainfall rate and the concentrations and mean sizes of raindrops. Uncertainties in the identification of ice particles were noted in section 2. There is an urgent need to determine whether the additional quantities that are measurable by state-of-the-art radars will permit discrimination among different types of ice particles or estimation of their sizes and concentrations. Both the scope and accuracy of verification studies must be significantly improved in order to deal more fully with the remaining uncertainties of rainfall measurements and

with the issues of ice phase and mixed-phase discrimination. Particular issues include the discrimination of wetted and unwetted ice particles, the sensitivity of measurements to the degree of orientation of ice particles, and the characterization of propagation effects in various meteorological conditions. Further questions will surely arise as examinations of newly measurable polarimetric quantities are undertaken.

Verification data can be obtained by measurements both in the laboratory and in the field. Laboratory facilities for the measurement of backscattering from known water and ice forms include one being developed by the Consiglio Nazionale delle Ricerche Fisica della Bassa e Alta Atmosfera (CNR-FISBAT) in Bologna, Italy, and at Niigata University and Toyohashi Institute of Technology in Japan. Measurements of backscatter from dielectric objects were also performed by Allan and McCormick (1978, 1980). Laboratory work of this type is complicated by the fact that measurements made on simulated or actual hydrometeors of complex shape or mixed phase at one frequency are not generally transferable to another frequency because of the frequency dependence of the refractive index of liquid water.

Verification studies in the field typically face problems associated with the degree to which in situ measurements are representative of those made, generally on a larger scale, by radar. Other difficulties may stem from the disrupting effects of airflow around an instrumented aircraft, which may prevent accurate observations of the shape or orientation of hydrometeors, or from uncertainty in the location of an aircraft, which complicates coordinated operation of radars and aircraft. Database measurements in the atmosphere can be made under conditions in which the microphysical characteristics of clouds or precipitation remain unchanged for extended periods of time and can be well defined by in situ measurements at the surface or aloft. The performance of such measurements in Hawaii has been proposed so that the height variation of microphysical parameters of warm rain can be documented by measurements along a mountain road. Observatories such as that operated by the University of Wyoming on Elk Mountain could also be used for such measurements.

The observation of lightning by radar presents some unique verification problems. Observations such as those of Geotis and Williams (1987) indicate that the major limit to detection at radar wavelengths of 10 cm or less is masking by precipitation, i.e., when the reflectivity factor due to hydrometeors is higher than about 35 dBZ. Lightning echoes can be observed at these wavelengths in the presence of precipitation by means of the cross-polarized received signal if a linearly polarized signal is transmitted. Polarimetric quantities such as the differential reflectivity and the cross-correlation of orthogonally polarized received signals should yield information about the spatial orientation of the lightning channels. One approach to the verification of such measurements is to observe by radar

the lightning discharges triggered by rockets with trailing wires. Triggered lightning, being both well controlled and visually verifiable, should provide reference data for the interpretation of copolarized and cross-polarized reflectivity and other polarimetric quantities.

The factors outlined here are only a few of the issues that make verification studies challenging to conduct and evaluate. Solutions to these problems will involve application of new technologies and analysis techniques. We recommend the convening of periodic workshops for detailed review and discussion of verification techniques. Topics for such meetings should include the adequacy of existing techniques, strategies for verification of specific polarimetric measurements, and technological needs for improved verification by either in situ or remote measurements.

### 3.4 Technological Improvements

We believe that the technology of most polarimetric meteorological radars now in use limits the quality of the resulting scientific research. In the United States the 3-cm radar at New Mexico Institute of Mining and Technology presently has full matrix polarimetric capability, and the 10-cm radar at Air Force Geophysics Laboratory is expected to have this capability in 1989. As noted in section 2, however, the full matrix capability is not the sole criterion of the state of the art. Improvements to existing facilities can be made within the present state of the art in such areas as antenna design, polarization control, receiver design, and data processing without any "breakthroughs" in the respective technologies. Hence we urge that existing facilities be improved in all these areas and that other radars in the United States be upgraded for full matrix measurement within the next five years. Pursuit of these goals should be closely coordinated with the planning of new facilities (see section 4).

Recent advances in several areas permit improvements in measurement capability beyond that of the best existing meteorological radars. The best antennas presently in use have linear copolarized and cross-polarized sidelobes near  $-30$  and  $-35$  dB, respectively, relative to the peak of the main lobe. Recent advances in the technology of phased arrays promise significant reduction of the cross-polarized radiation generally associated with these antennas. Thus phased arrays, which typically have very low copolarized sidelobes, may become feasible for polarimetric applications. Technological advances may also permit a given performance level to be achieved at lower cost. For example, the circular waveguide horn described by Lee et al. (1988) may be a low-cost broadband alternative to the Potter horn or the corrugated horn. Advances in electronic (nonferrite) switches promise both higher power capacity and more rapid switching than are now available. The use of a radome is usually detrimental to the quality of measurements, and most high quality polarimetric radars op-

erate without radomes. For those facilities requiring radomes, additional research should be conducted on the resulting effects on cross-polarized radiation. Finally, advances in receiver technology, such as the development of high dynamic range mixers and improvements in filter characteristics resulting from computer-aided design, should be incorporated in the design of new meteorological radars and in the upgrading of existing radars.

### 3.5 Operational Applications

The differential reflectivity techniques for rainfall measurement and hail detection are being evaluated in Italy and Japan with the goal of operational implementation in the relatively near future. Operational techniques are also being developed and evaluated in the United States (Lip-schutz et al., 1986). There are concerns, particularly in the United States, that these techniques have not been demonstrated adequately. Hence, long-term, wide-area demonstrations of these techniques are needed, analogous to the Joint Doppler Operational Project in 1977-79, which was a key step toward the initiation of the Next Generation Weather Radar (NEXRAD) Program. These demonstrations will require the involvement of operational user agencies and detailed comparisons with present operational techniques. The NASA TRMM offers an opportunity for an operational demonstration in the tropics. Other operational demonstrations should be conducted in middle latitudes, in both mountainous and flat terrain. The evaluation of operational techniques can be greatly aided by the development and testing of these techniques in Italy and at the Public Works Research Institute in Japan. Although these efforts involve only differential reflectivity radars at present, they offer the potential of expansion in the future.

There must be a related effort to refine both the measurement concepts and the radar system concepts appropriate to operational applications. Although the differential reflectivity is the most commonly suggested parameter for operational application, the relative merits of other quantities can and should be evaluated theoretically, experimentally, and in terms of their impact on radar system design and operation. For example, the linear depolarization ratio may be a better indicator of the presence of hail. Issues such as long-term reliability, simplicity of operation, and cost of components and systems must be addressed. For example, are antennas with very low sidelobes and high isolation between polarizations affordable for operational use? Are switchable circulators incorporating ferrite phase shifters sufficiently reliable for operational use? How do absolute and differential calibrations affect operational results? How do the constraints of operation on an aircraft or a satellite affect measurement capabilities? With the continuing high level of interest in operational applications, we envision an ongoing process of transfer of technology from research into operations as techniques and compu-

nents are improved and as new operational requirements develop.

#### 4 UNITED STATES NATIONAL POLARIMETRIC RADAR FACILITY

The development of a national polarimetric radar facility in the United States is the most divisive issue we faced as a panel. Proponents suggest that such a facility include coherent dual-channel radars with fast polarization switching at several wavelengths from 10 cm through 8.6 mm and perhaps 3.2 mm. It could serve the purposes of 1) meteorological research, 2) education in meteorology and engineering, and 3) technological development. The radar facility might constitute one component of a major center for remote sensing, a center that would support scientists and engineers seeking to develop and apply a variety of remote sensing techniques.

Those who urge the development of such a facility in the near future emphasize 1) that a high-quality polarimetric radar facility is essential to support research and educational programs in the United States, 2) that the upgrading of existing radars to the technological state of the art is extremely difficult, and 3) that the cost of either a major upgrading or a new polarimetric radar facility is beyond the resources of any one research organization. Those who oppose such a development in the near future, most of whom favor it at a later time, maintain 1) that such a development requires broad support that does not yet exist in the meteorological research community, 2) that the funds necessary for such a development are better spent, at least in the next five years, on the upgrading and expanded use of existing radars, and 3) that radars under the direct control of scientists or engineers in research organizations are likely to be more effectively used, both in research and in education. Many issues must be resolved in order to progress toward the specification of such a facility. For example, what remote and in situ sensors and analytical capabilities should it comprise? Should it be managed by NCAR, by the National Science Foundation as a facility separate from NCAR, by an academic consortium, or by an interagency governmental organization? Should it be tied in any way to a specific program such as TRMM? Where should it be based? Should individual radars be transportable for use at several locations? These questions produce a variety of opinions among members of the panel.

The principal obstacles to the development of a U.S. national facility at this time appear to be 1) lack of a clear understanding as to what the facility should be and 2) lack of broad-based support from the meteorological research community. A well-formulated plan, representing a consensus of meteorological radar specialists, would provide the basis for gathering financial support from several government agencies. Broad-based meteorological

support would improve the prospect for this facility in competition with other research needs. Much of what we recommend in the preceding and following sections will serve to break down these obstacles within the next few years.

#### 5 SCIENTIFIC INTERACTIONS

As emphasized in the Introduction, vigorous scientific input or "cross-fertilization" is a critical component of the development and application of polarimetric radar techniques in meteorology. This field has benefited greatly from strong ties to the fields of communications engineering, atmospheric propagation research, and military radar research. While there have been valuable interactions with disciplines such as cloud and precipitation physics, mesoscale meteorology, and hydrology, we believe that these interactions must be significantly broadened to guide the development of polarimetric facilities and techniques properly. A variety of specific research goals has already been described; progress toward attaining them would be well served by broadened scientific interactions. We suggest several mechanisms to foster these interactions:

- Descriptive articles in publications such as the *Bulletin of the American Meteorological Society*, *Eos* (American Geophysical Union), and *Spectrum* (Institute of Electrical and Electronics Engineers) would serve to familiarize the entire meteorological and engineering communities with current developments of polarimetric radar techniques. Similar articles or notes in "popular" scientific publications and trade journals would reach an even broader audience.

- Participation in facility development, field programs, and data analysis are important components of professional education. Funding agencies and facility managers must work together to provide opportunities for temporary visitorships and exchange programs that maximize the use of facilities. Coupling such opportunities to academic programs could serve to strengthen education in this area.

- The informal series of workshops on polarimetric radar techniques in meteorology should continue. Organization of future workshops should include participation not only by radar specialists but also by scientists and engineers working in cloud physics, precipitation measurement, mesoscale meteorology, and other related topics. Potential workshop topics include facility performance, verification techniques, analysis techniques, and cloud and precipitation studies.

#### 6 SUMMARY

Polarization diversity radar techniques are capable of revealing information about microphysical processes in clouds and precipitation at an otherwise inaccessible level of detail. Until very recently, polarimetric measurements have generally been limited to the absolute reflectivity and

either the differential reflectivity or the depolarization ratio and cross-correlation. The differential reflectivity has yielded some improved estimates of rainfall rate and has proven valuable in identifying the ice phase in clouds. We expect that more complete measurements; e.g., comprising reflectivity, Doppler velocity parameters, power ratios, and cross-covariances, will yield a better understanding of glaciation and melting processes, more detailed descriptions of ice-phase hydrometeors, and identification of electrification effects. The major challenges we face are to develop and refine theory for interpreting these quantities, to perform the measurements in various meteorological situations, and to verify the interpretations.

We recommend that:

- Polarimetric radars be more effectively used in meteorological research, both in large field programs and in locally managed programs. The more effective use of these radars requires increased interaction between polarimetric radar specialists and the broader meteorological research community, particularly in the areas of cloud physics and mesoscale meteorology. These interactions will also provide the basis for further development of operational applications.

- Verification techniques be developed and refined. These techniques should include not only measurements by particle instruments on aircraft and on the ground but also intercomparison with other remote measurements and with numerical model calculations. This is an important subject for technical workshops.

- Much better use of available radar technology be made in meteorological research radars. Existing radars should be improved to permit full matrix measurements.

- A substantial effort be devoted to the planning of a national polarimetric radar facility in the United States. The first step toward this goal will be to develop a consensus on the scientific need, specific capabilities, mission, and management.

Polarization diversity radar technology, both in meteorological radar systems and in the interpretation of meteorological measurements, has experienced significant recent progress. We must build on these advances to increase our knowledge of cloud and precipitation physics and ul-

timately to translate that knowledge into beneficial applications.

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## APPENDIX: LIST OF ACRONYMS

|         |  |
|---------|--|
| CCOPE   | Cooperative Convective Precipitation Experiment                                |
| CHILL   | University of Chicago/Illinois State Water Survey                              |
| CINDE   | Convective Initiation and Downburst Experiment                                 |
| CLAWS   | Classify, Locate, and Avoid Wind Shear (Project)                               |
| DFVLR   | Deutsche Forschungs- und Versuchsanstalt für Luft und Raumfahrt (West Germany) |
| IFA     | Istituto di Fisica Dell'Atmosfera (Italy)                                      |
| ISWS    | Illinois State Water Survey  |
| MAYPOLE | May Polarization Experiment  |
| MIST    | Microburst and Severe Thunderstorm (Project)                                   |
| MIT     | Massachusetts Institute of Technology  |
| NASA    | National Aeronautics and Space Administration                                  |
| NCAR    | National Center for Atmospheric Research                                       |
| NEXRAD  | Next Generation Weather Radar  |
| NOAA    | National Oceanic and Atmospheric Administration                                |
| NRC     | National Research Council (Canada)   |
| NSSL    | National Severe Storms Laboratory  |
| PROFS   | Program for Regional Observing and Forecasting Services                        |
| STORM   | Stormscale Operational and Research Meteorology (Program)                      |
| TRMM    | Tropical Rainfall Measurement Mission  |